TRENDS IN AIRCRAFT EFFICIENCY AND DESIGN PARAMETERS

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ABSTRACT

Developing an aircraft CO_2 candidate metric and subsequent compliance assessment requires an understanding of practices and trends in aircraft design. Historically, fuel burn has been an important consideration for airlines, and manufacturers have responded by developing technologies to improve the efficiency of new aircraft designs. However, market forces also demand improvements in aircraft performance beyond reduced fuel burn. As a consequence, some portion of efficiency gained through improved technology has been devoted to increasing other aircraft design parameters such as range, maximum payload, and speed rather than to reducing emissions on a constant mission.

In this paper, we discuss some initial ICCT work on sales-weighted historical trends in new aircraft design attributes and their influence on aircraft efficiency, using design range as a first area of inquiry. We show that aircraft design parameters that influence fuel efficiency have changed over time, both in aggregate and for specific replacement designs, and therefore need to be taken into account when developing a CO_2 certification requirement and stringency scenarios for further consideration. We also present evidence that commercial aircraft are not typically operated near their maximum performance points (i.e. design range and max payload), and therefore setting a CO_2 certification requirement and standard at those points may overestimate improvements in future designs.

1. INTRODUCTION

Developing an aircraft CO_2 candidate metric and stringency scenarios will require knowledge and understanding of a complex system. Proper design choices will not only result in a policy that underscores environmental performance accurately, but also one that minimizes costs, undesirable impacts on competitiveness, and potential standard gaming. Although not continuous from a sales weighted delivery perspective, commercial aviation's gains in environmental performance and efficiency gains have been significant. To ensure continual improvement, a properly designed metric and stringency should be a key component of efficient design and operational choices.

Aircraft are a system of interconnected disciplines including structures, aerodynamics, and engine technologies among others. An analysis of historical trends can inform and support both aircraft level and fleet operational and design choices that have provided environmental benefits and those that have not. Once identified, trends and variables that show important influences can be isolated and further evaluated. These may include changes in range, payload, materials, and aircraft utilization. Here we present our work on summarizing historical trends and presenting an initial assessment for some identified aircraft parameter(s).

2. METHODS

New aircraft historical trends were analyzed using a data set of annual aircraft deliveries purchased from Jet Information Services along with Piano-5, an aircraft emissions and performance software suite.[1] A detailed methodology description is provided in "Efficiency Trends for New Commercial Jet Aircraft: 1960 to 2008."[2] Unless noted, all other methods were similar as listed in that paper. Regional jets were defined as aircraft having less than 104 seats and/or as self-proclaimed.[3] The plane files that had different designations in Piano 5 than those in Piano-x are listed in Table A-1 in the Appendix. All reported values are sales weighted averages. Default Piano values for all parameters, including available flight levels, cruise mach, and taxi times were used for all analysis unless otherwise listed. Energy consumed was calculated for nominal design range at design payload (default maximum passenger load). Maximum payload was calculated from the operating empty weight OEW and maximum zero fuel weight (MZFW).

For investigating the match of aircraft model to mission, payload-range operations data for the Airbus A320, Boeing 737, and Boeing 777-200, and Airbus A300-600 freighter were obtained from the US Department of Transportation Bureau of Transportation Statistics Form 41 Schedule T100 for December of 2006 including both domestic and international flights. Payload-Range diagrams were set at default Piano parameters unless otherwise stated.

The sensitivity of aircraft fuel efficiency to changes in design range was quantified through a 10% reduction in design range. An overview of the method for range design is provided in the Appendix. For all range re-designs, thrust to weight and wing loading were maintained to the original Piano values. This in essence was a simplified re-design focusing on reduction of fuel requirement with wing and engine “rubberization.” This re-sizing analysis was performed for Airbus A320 and A380 and for Boeing 737-800, 777-200ER, and the 787-8. To assess changes in energy consumption, these re-sized aircraft were “flown” at 99% maximum SAR with all other default Piano settings at 1500 kg payload and 2600 km mission length for narrowbody aircraft and 35000 kg payload and 8800 km mission length for widebody aircraft. These payload-range combination were used because they covered approximately 75% of the RITA reported missions for the B737 (narrowbody representative) and the 777-200ER (widebody representative). Sensitivity to design range reduction for the 777-200ER was performed for the same payload-range combination stated above at 4 different reductions in design range.

3. **RESULTS**

3.1 Historical Trends

As shown in Figure 1a, the estimated average energy efficiency of newly delivered narrowbody aircraft improved significantly from 1960 to 1988, with fuel burn per ASK at design range decreasing approximately 48%, an annual reduction of 2.3%.[4] However, from 1989 to 2008 improvements have been much more limited. As discussed in CAEP/8-IP/17, this corresponds to a fall-off in the number of new aircraft types being brought to market, as well as the increasing number of deliveries of regional jets (RJs) within the same time period (Figure 1d). This is indicative of the more energy intensive nature of the smaller regional aircraft as delivered, where for example the average consumed energy for RJ’s (business jets excluded) is more than 30% greater than for larger narrowbodies of the Piano aircraft analyzed. Similar to narrowbody aircraft, widebody aircraft showed significant improvement over a similar time span (1.8% annually, 30% reduction in energy use). The lack of significant improvement for widebody aircraft in energy

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[1] See www.lissys.demon.co.uk/Piano5.html for details.

[2] Available at http://www.theicct.org/information/reports/efficiency_trends_for_new_commercial_jet_aircraft_1960_to_2008

[3] i.e. if the model name contained RJ/regional jet as proclaimed by manufacturer.

[4] Annual reduction averages are reported for comparison and do not imply continuous reductions.

consumption beyond 1990 corresponds to an increase in nominal design range, no increase in average available seats, and an increase in maximum payload (Figures 1b and 1c).

The historical trends suggest the dependence of the environmental performance of new aircraft on a multitude of design and performance variables. Of particular note is the correlation between payload-range and delivered aircraft fuel efficiency, which will be further explored in the next section. This aggregate trend also holds for specific cases of aircraft replacement: the design parameters of new aircraft deviate, often significantly, from those of the aircraft they replace. As one commercially important example, consider the payload range diagram of the Boeing 787-8 compared to two 767-300ER variants, shown in Figure 2. For the lighter 172 tonne MTOW variant, max payload has been increased by 7.5 tonne (22%), and design range by 5500 km (65%). For the heavier 767-300ER variant, maximum payload has been held virtually constant, while design range has been extended by 3500 km (34%). Figure 2 demonstrates that even nominally "replacement" aircraft may have dramatically different payloads and ranges. Identifying technologically feasible stringency scenarios will therefore require an understanding of the sensitivity of aircraft efficiency to design parameters such as design payload and design range when flown on representative missions.

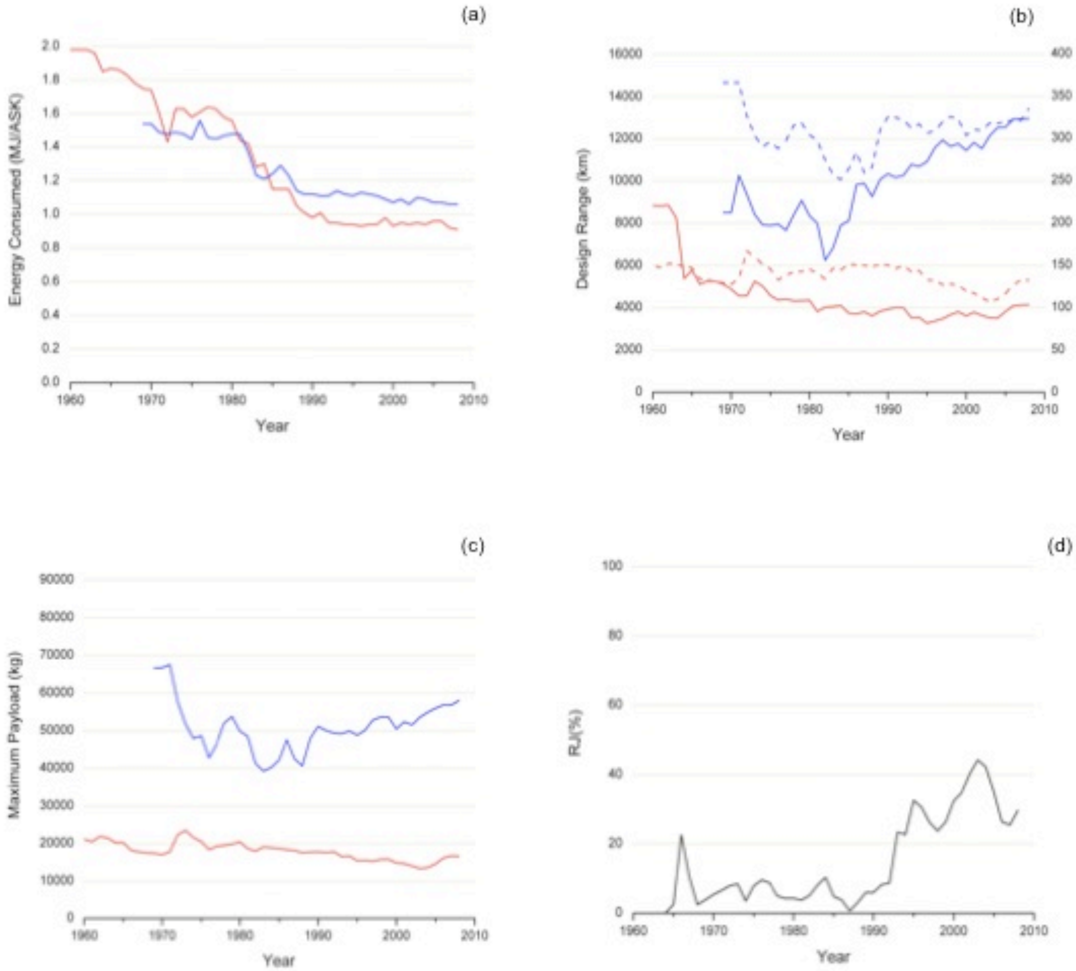

Figure 1 Historical trends for newly delivered aircraft. (a) Estimated energy consumption at design payload and range left axis,(b) Range at design payload, solid lines left axis; estimated number of available seats, dashed lines right axis, (c) Maximum payload, and (d) Regional jet deliveries**.** For all: Red lines narrowbody, blue lines widebody.

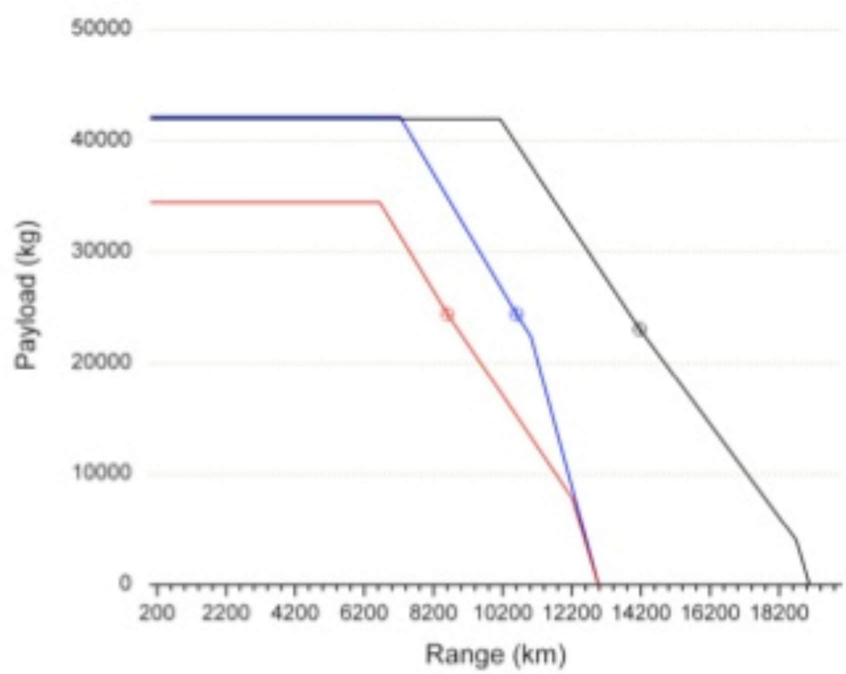

Figure 2: 767-300ER vs. 787-8 payload/range diagrams. Lines: black B787-8, blue b767-300ER(187 tonne), and red B767-300ER(172 tonne). Crossed circle denotes nominal design payload and range. All parameters at default Piano values.

3.2 Match of Aircraft Model to Mission

A payload-range diagram illustrates the interconnectivity of these two parameters (Figure 3) alluded to in the historical analysis. In essence, to carry more payload (passengers), range is sacrificed and vice versa to increase range, payload (passengers) is sacrificed. This diagram is an important representation in determining aircraft efficient design and operation in terms of payload and range performance. For example, Figure 3 plots the payload and mission lengths flown for December 2006 as obtained from the BTS Form 41 T100 data for both international (in- and outbound) and domestic flights for selected passenger and freighter aircraft.

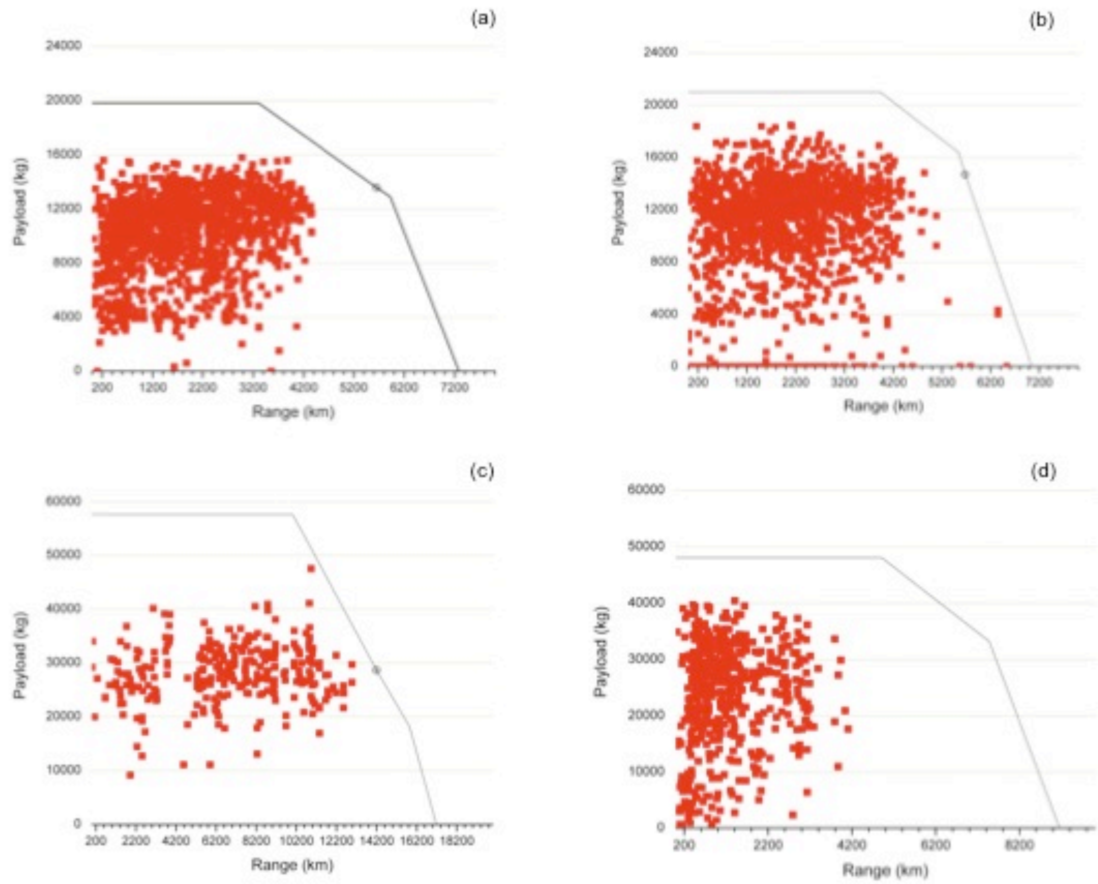

Figure 3 Payload-Range Diagram for (a) Airbus A320-200, (b) Boeing 737-800, (c) Boeing 777-200ER, and (d) Airbus A300-600 Freighter for two major all freight operators. Red data points are point-to-point flights from BTS T100 data for December 2006.[5]

As shown, no flights were operated at either limits of maximum payload or maximum range with essentially a "void" region of payload-range operation existing for all aircraft in the figure. This void region is represented more clearly in Figure 4, which distils the BTS data into 200 km distance increments with average payloads and corresponding frequencies. The blue crosshatched region in the figure highlights an essentially unused performance potential for the aircraft when comparing actual operations to aircraft design potential. The reasons for this are complex and not the main focus of this study, however reoccurrence of this unused performance may highlight inefficiencies including:

1. A "one size fits all" design approach under which aircraft are sized to meet extreme rather than representative payload-range missions, leading to inferior environmental performance during actual operation.

2. Excessive operational inefficiency contingency (e.g. airport congestion and ATC, long diversion distances, higher speed).

3. Commonality in engines/wings/fuselage.

[5] Average payload for each flight calculated at 100 kg per passenger and the inclusion of any freight reported.

4. Density of cargo/freight (volume limitation rather than mass limitation).

5. Other?

These unapplied payload-range combinations suggest that modern jet aircraft are oversized relative to their in-service operation. On the design level, this results in an unnecessarily heavy aircraft that burns excess fuel on most missions. Designing a CO_2 standard that recognizes potential improvements from aircraft "rightsizing" and promotes those emission reductions in addition to efficient technologies is a key challenge for ICAO.

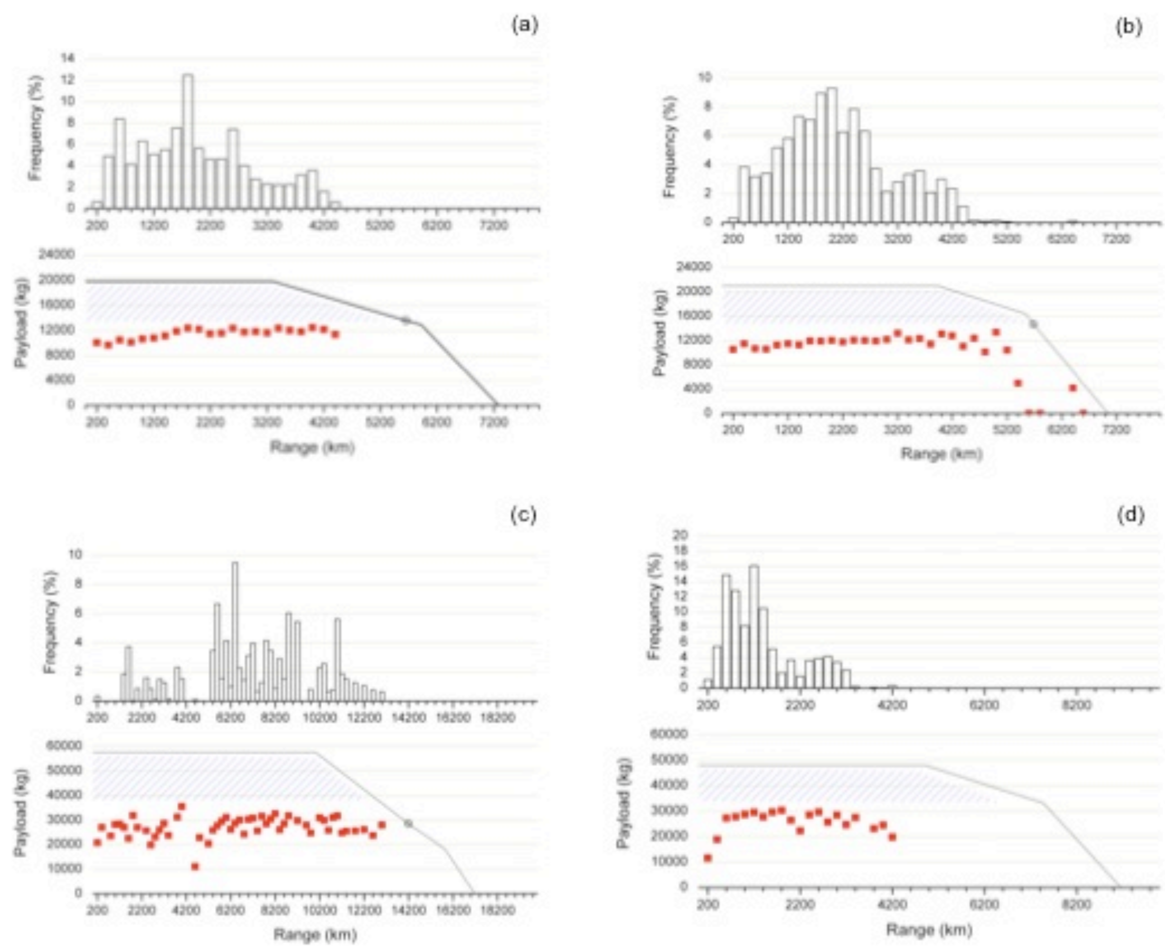

Figure 4 Payload-Range diagrams with 200km incremental actual operational frequencies from BTS T100 data for (a) A320-200, (b) B737-800, (c) 777-200ER, and (d) A300-600 Freighter configuration for two major express freighter operators.

Figure 4 holds implications for the design of an aircraft CO_2 certification requirement and standard, namely that a certification "test point" set at or near an aircraft's maximum range and/or payload may not provide the best reflection of actual in-service efficiency. This point is illustrated in more detail in Figure 5, which shows Piano-X estimated efficiency improvements of the 737-700 (Figure 5a) and the 787-8 (Figure 5b), as a function of payload and range, relative to B737-300 and the

B767-300ER respectively (variants that each next generation aircraft might replace).[6] While further work is needed, this figure suggests that the efficiency improvements for both aircraft are disproportionately high at high loads and long ranges, meaning that a standard set at those operational levels would likely lead to fewer real world reductions than anticipated. This finding may also be generalizes to efficiency metrics set as a function of MTOW, given that MTOW denotes an operational regime that is rarely met in practice.

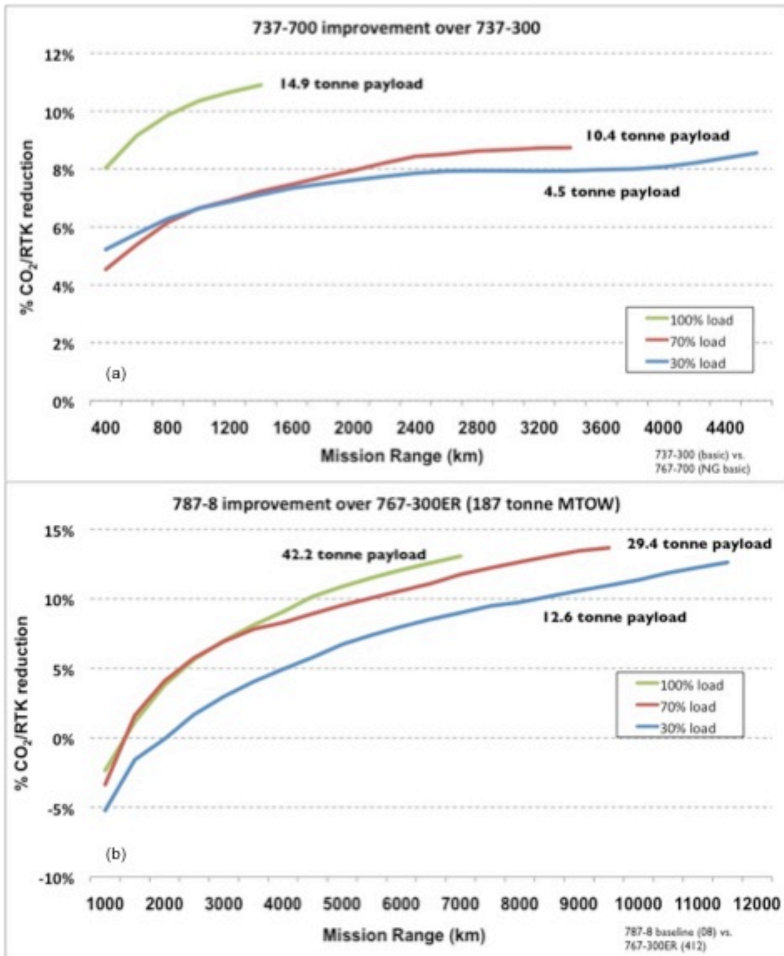

Figure 5 Relative block CO2 intensity reductions by mission range and payload for (a) B737-700 v. 737-800 and (b) 787-8 v 767-300ER.

3.3 Sensitivity of aircraft efficiency to design parameters

Section 3.1 showed how certain aircraft design parameters may be changing over time. For those changes to be relevant to the development of a CO_2 standard, however, those changes must be linked to variations in aircraft fuel efficiency. This section aims to show this, taking the relatively "simple" variable of design range as an illustrative example.

In this section, we describe initial work to test the sensitivity of aircraft fuel efficiency to reductions in design range. Our method of analysis, which relies upon reducing maximum fuel weight, "rubberizing" and downsizing engines and wings, and estimating a new, lower OEW aircraft, is described in further detail in the Appendix. Figure 6 is a graphical representation of ways to test

[6] 99% SAR, reserves as per CAEP8-WG3-IP7-05, otherwise default Piano-X values for all parameters.

the effect of changes in design/operational variables on aircraft fuel efficiency, as represented on a payload-range diagram. As shown the efficiency potential of these untapped, higher efficiency performance regions may be accessed by increasing design payload, reducing design range, decreasing maximum payload, or increasing design payload and decreasing range. Note that the sizes of the changes have been exaggerated here for emphasis. As previously mentioned, payload and range are highly linked in terms of aircraft performance. However, for this study, the focus remains on nominal design range. Other scenarios, including reductions in maximum payload in order to better match operational conditions, will be addressed in future ICSA work.

Table 1 lists the response to range reductions for a single range point and both narrow and widebody aircraft. This is a first approximation approach designed to maintain takeoff field length and landing field length. As listed, efficiency gains of 0.3 to approximately 2.8% can be achieved by reducing range by 10%. Figure 7 illustrates the efficiency gains possible for a range of nominal design range changes for the B777-200ER. The data shows near linear response in the range variations considered with a slope of approximately 0.1 on a % change by % change basis.

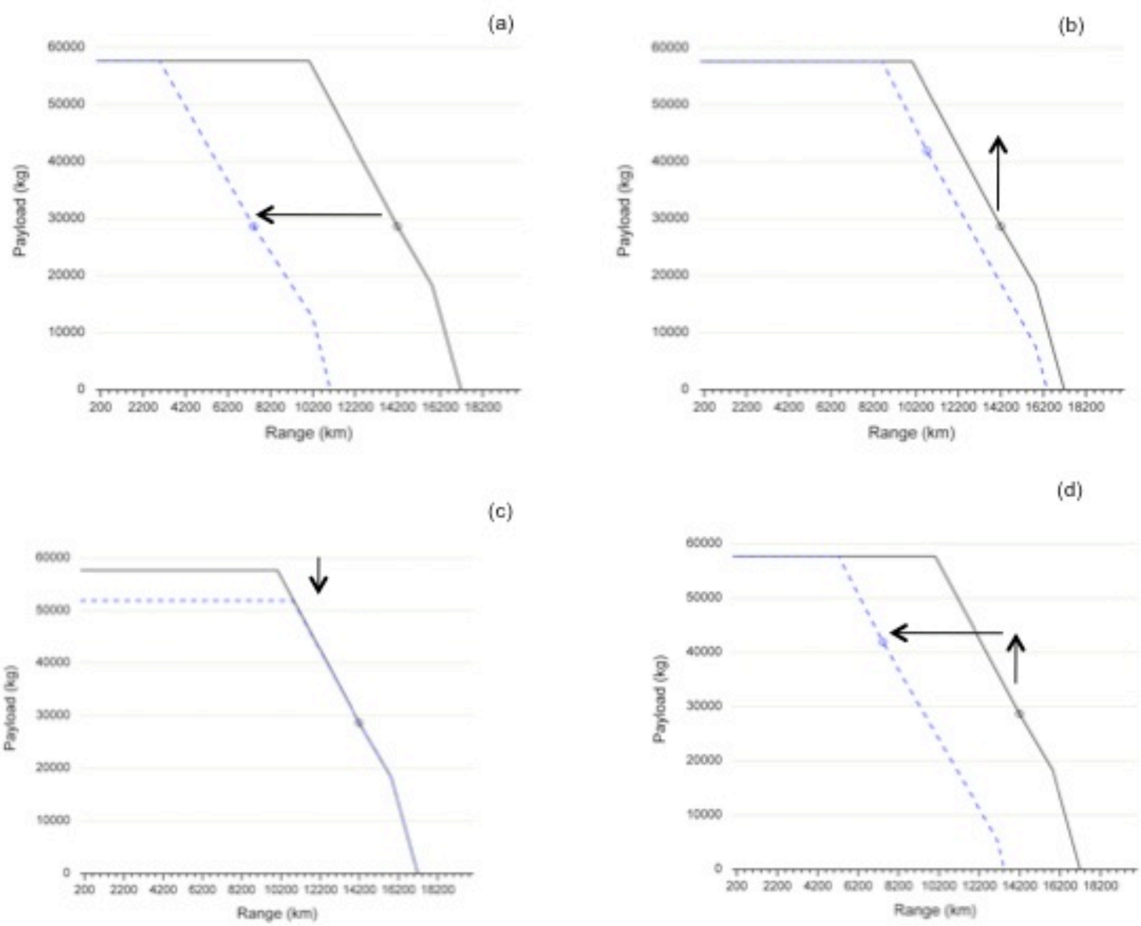

Figure 6 Schematic representation of variation in payload-range (a) nominal design range change, (b) nominal design payload change, (c) maximum payload reduction, and (d) both increase design payload and decrease in range change.

Table 1 Scenario reductions for five representative aircraft

Aircraft	Design Range Change (%)	Operating Empty Weight Change (%)	Structural Efficiency Change (OEW/MTOW %)	Corresponding Change in Energy Consumption (%)
Airbus A320-200	-10.	-2.0	1.6	-0.3
B737-800	-10.	-3.9	2.7	-0.7
B777-200ER	-10.	-3.6	3.9	-1.2
B787-8	-10.	-1.5	3.7	-0.3
A380-800	-10.	-4.5	3.7	-2.8

Mission parameters as defined in Section 2.

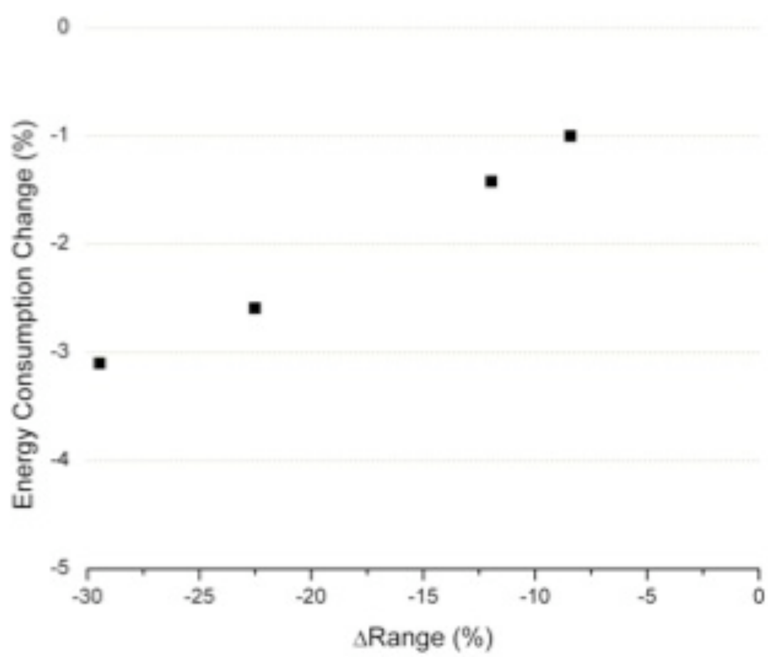

Figure 7 Range sensitivity analysis for 777-200ER.

These reductions can be assumed to be a minimum value as this simplistic redesign approach is a resizing exercise without full aircraft re-optimization at the new lowered design range. This is evident in the structural efficiency (as measured by OEW/MTOW) of the lower range aircraft in fact decreasing by up to 3.7%, which may indicate untapped areas of mass reduction (Table 1). Furthermore, our limited aircraft sample size may be underestimating the degree to which fuel efficiency improves as OEW falls. Literature suggests that a 1% decrease in OEW should yield 0.25~0.75% improvements in fuel efficiency[7], while other preliminary work by ICSA on matched freighter-passenger aircraft models shows a 0.6% fuel efficiency improvement by a 1% OEW drop (at original OEW design payload and range). This is approximately double the value of ~0.3% boost in fuel economy per 1.0% reduction in OEW shown in Figure 7. This work will be presented at future meetings. Finally, an ad hoc analysis of in-service aircraft, not presented here due to space limitations but that could be developed for future WG3 meetings, suggests that the elasticity of

[7] Lee et al. *Annu. Rev. Energy Environ.* 2001 26; 167-200.; Babikian et at. *J. Air Trans. Management* 2002 8;389-400.

aircraft fuel efficiency to design range over medium-haul missions may be a factor of two or more higher than that presented here.

It should however be clear that design range can have a profound influence on aircraft performance and hence emissions, and we expect that a similar relationship will hold for maximum payload. Both will need to be considered when developing metric alternatives and stringency scenarios for a CO_2 standard.

4. DISCUSSION AND IMPLICATIONS

This paper holds two main implications for the development of a CO_2 certification requirement and the identification of stringency scenarios for future analysis. First, commercial aircraft do not appear to be typically operated near their maximum performance points (i.e. design range and maximum payload), and measuring efficiency of aircraft at this point may overestimate efficiency improvements from future designs. While further work is needed, this may also apply to an efficiency metric based upon MTOW and maximum range, which reflects extreme rather than representative missions. Certification test point(s) near actual operational conditions are more likely to provide an accurate representation of in-service efficiency and real improvements due to the introduction of new equipment under a standard.

Second, aircraft design parameter values, including design range and payload, change over time in a way that influences aircraft efficiency. This is true of even nominally equivalent replacement aircraft, as typified by the 737-700 and 787 replacement of the 737-300 and 767 family, respectively. As such, design parameters that accurately reflect these influences need to be incorporated into a CO_2 certification requirement and efforts to develop stringency scenarios for a standard. ICSA recommends further WG3/CO_2 task group work on this topic, and look forward to contributing to that discussion.

APPENDIX

Table A-1 Piano 5 and Piano-x plane name changes

Piano-x Designation	Piano 5 Designation
Airbus A380-800 (v08h)	Airbus A380-800 (v09h)
B747-400 (875)	B747-400 (875)p
B747-400 (875)	B747-400 (875)p
B747-400ER (910)	B747-400ER (910)g
B767-200 basic	B767-200(300) v87
B767-200ER	B767-200ER(387) v87
B767-300	B767-300(350) us
B767-300ER	B767-300ER (380)
B767-400ER basic	B767-400ER (400)
B777-200 ER (max)	B777-200ER (656)r
B777-200 LR (max)	B777-200 LR (766)
B777-200 LR (v04)	B777-200 LR (710)
B777-300 ER (v04)	B777-300 ER (775)
Embraer 170 LR (v07)	Embraer 170 LR
Embraer 190 AR (v07)	Embraer 190 AR
Embraer 190 LR (v07)	Embraer 190 LR
Embraer 190 STD (v07)	Embraer 190 STD

Range Re-Design

Piano is a sophisticated aircraft analysis tool that allows for aircraft design or modification of an existing design. Modification can be achieved through the use of existing plane files representing past, current, and future aircraft designs with the ability to change several hundred user defined parameters. Here we present the procedures used for a simplistic re-design around an altered design range. This is in no way exhaustive in terms of Piano capabilities and for full and further detail the Piano user and help files (available at http://www.lissys.demon.co.uk/index2.html) are highly recommended.

For range redesign, all default Piano parameters were used unless stated otherwise. Resizing was achieved by maintaining thrust-to-weight (T/W) and wing loading (W/S) of the original aircraft. This maintains landing and takeoff field lengths while at the same time "rubberizing" the engines to produce a lowered reference thrust. Thus upon reducing range, less fuel is required, which reduces both weight directly through lower fuel capacity requirements and indirectly by reducing stresses and thus required structural support weight. Since aircraft wings and engines are largely sized for takeoff at highest MTOW (other considerations may include climb requirements for example), this weight reduction in turn allows for lowered lift requirement resulting in wing and engine resizing, which in turn has further effect and ultimately a reduction in operating empty weight. This description highlights the interconnectivity of a multitude of parameters and the cascading effects on improvements/efficiencies.

Table A1 lists some pertinent parameters as described above for the B777-200ER range resizing listed and changes to those upon redesign for different nominal range. As shown, a reduction in weight reduces fuel requirements and ultimately resulting in a lowered operating empty weight. It should also be noted that this resizing can be performed without these affect on the design payload or maximum payload of the original aircraft.

Figure A1 illustrates the changes described above. As shown, the reductions in fuel weight and structural supports also results in reduction in wind size. The figure also illustrates the reduction in range as shown in the payload-range diagram.

Table A 2 Changes in listed parameters with B777-200ER 22% range reduction

Parameter	Original Aircraft	Range Reduced Variant	Change (%)
T/W	0.280	0.280	0
W/S	151 lbsf	151 lbsf	0
OEW	141884 kg	130397 kg	-8.1
Fuel Volume	45220 USG	34386 USG	-24.
Maximum Payload	57697	57697	0
Design Payload	28672	28672	0

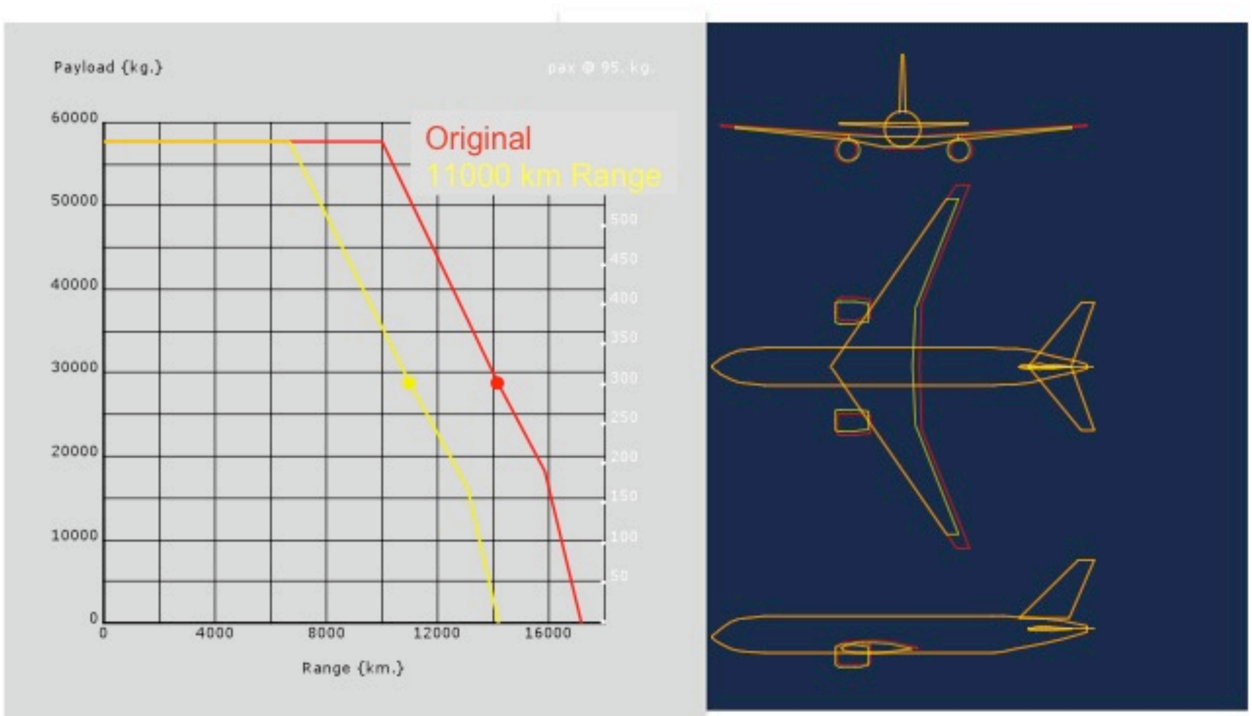

Figure A 1 Payload-Range diagram and 3-view profile for B777-200ER range re-size.